EFFECT OF SPECIMEN SIZE ON FRACTURE TOUGHNESS OF MILD STEEL

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ABSTRACT

This project was conducted to investigate the effect of specimen size on fracture toughness of mild steel. Fracture toughness is an indication of the amount of stress required to propagate a pre-existing flaw. It is a very important material property since the occurrence of flaws is not completely avoidable in the processing, fabrication, service of a material or component. In this experiment, the specimen size was chosen as a main parameter to analyse the fracture toughness of mild steel. The specimen size was divided into two parameter to be investigated, there is thickness and notch depth of the specimen. The specimen geometry was referred to the ASTM E399-74 standard and the test applied for the fracture toughness is single edge notch bending. From the test results, when the thickness of the specimen increase the fracture decreases until the thickness reach the critical dimension and the fracture was become constant. For the notch depth, when the notch depth decreases the fracture of the specimen also decreases until the notch depth reach the critical dimension and the fracture toughness was become constant. The thickness and notch depth of the specimen is main parameter to analyze the fracture toughness of the material or specimen because each of the specimens will reach the critical dimension and constant the fracture toughness value.

ABSTRAK

Projek ini telah dijalankan untuk mengkaji kesan saiz spesimen ke atas keliatan patah keluli lembut. Keliatan patah merupakan satu petunjuk kepada jumlah tekanan yang diperlukan untuk menyebarkan kecacatan pada bahan. Ia adalah sifat kecatatan bahan yang tidak dapat dielakkan sepenuhnya dalam pemprosesan dan fabrikasi bahan atau komponen. Dalam eksperimen ini, saiz spesimen telah dipilih sebagai parameter utama untuk menganalisis keliatan patah keluli lembut. Saiz spesimen telah dibahagikan kepada dua parameter yang untuk dianalisis iaitu ketebalan dan kedalaman takuk spesimen. Geometri spesimen adalah mengikut kepada standard ASTM E399-74 dan ujian yang digunakan untuk mengalisis keliatan patah 'single edge notch bending'. Daripada keputusan ujian, apabila ketebalan spesimen meningkatkan keliatan patah berkurangan sehingga ketebalan mencapai dimensi kritikal dan menyebabkan keretakan itu menjadi malar. Manakala untuk kedalaman takuk pula, apabila kedalaman takuk berkurang keliatan patah pula menurun sehingga kedalaman takuk mencapai dimensi kritikal dan keliatan patah menjadi malar. Kedalaman takuk dan ketebalan spesimen adalah parameter utama untuk menganalisis keliatan patah bahan kerana setiap spesimen akan mencapai dimensi kritikal dan menyebabkan keliatan patah menjadi malar.

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CHAPTER 1

INTRODUCTION

1.1 PROJECT BACKGROUND

Fracture toughness is an indication of the amount of stress required to propagate a pre-existing flaw. It is a very important material property since the occurrence of flaws is not completely avoidable in the processing, fabrication, or service of a material/component. Flaws may appear as cracks, voids, metallurgical inclusions, weld defects, design discontinuities, or it is common practice to assume that a flaw of some chosen size will be present in some number of components and use the linear elastic fracture mechanics (LEFM) approach to design critical components. This approach uses the flaw size and features, component geometry, loading conditions and the material property called fracture toughness to evaluate the ability of a component containing a flaw to resist fracture. Fracture toughness, in the most general of definitions, is the ability of a material to withstand fracture in the presence of cracks.(NDT Resource Center, 2008)

Fracture toughness is measured in terms of K_{IC} (plane-strain fracture toughness) where K stands for stress intensity factor at the crack tip, I- denotes that the fracture toughness test is performed in tensile mode and C-denotes that the value of K is critical. When K attains critical value then crack propagation becomes unstable and results in fracture of the components. K_{IC} is a basic material property like yield strength. (M.O. Lai,1984)

This project is to investigate the fracture toughness or the basic material property of mild steel. Mild steel is the most common form of steel as its price is relatively low while it provides material properties that are acceptable for many applications. Mild steel has low carbon content (up to 0.3%) and is therefore neither extremely brittle nor ductile. It becomes malleable when heated, and so can be forged. It is also often used where large amounts of steel need to be formed, for example as structural steel. Although, the material is use in many application the toughness of the material or the product is important to be investigated, to make sure the product will run and operate safety. In this project, the material fracture toughness is investigated in term of specimen sizes by using Single Edge Notch Bend test. The specimen size is characterized into two parameter; which is specimen thickness and notch depth. Each of the parameter will give the different value of critical dimension and fracture toughness in order to produce the toughness material. When the productions and industries used the mild steel, the testing procedure is needed to produce effective, toughness and safety product.

1.2 PROBLEM STATEMENT

Mild steel is very important material used in automobile production. Automotive chassis is considered to be one of the significant structures of an automobile. It is usually made of a mild steel frame, which holds the body and motor of an automotive vehicle. More precisely, automotive chassis or automobile chassis is a skeletal frame on which various mechanical parts like engine, tires, axle assemblies, brakes, steering are bolted. At the time of manufacturing, the body of a vehicle is flexibly molded according to the structure of chassis. Automobile chassis is usually made of mild steel. It provides strength needed for supporting vehicular components and payload placed upon it. Automotive chassis or automobile chassis helps keep an automobile rigid, stiff and unbending. Therefore, the strength and toughness of the car chassis is very important parameter to analyze before built the car chassis due to avoid the crack occur when load is exerted. This research tries to investigate that the effect of specimen size on fracture toughness of material used in chassis manufacturing in order to get the critical dimension. The load was becomes constant when the part dimension is at critical dimension. Furthermore, this research is conducted to determine the fracture toughness of the mild steel with bending test in term of specimen thickness and notch radius to the automobile chassis.

1.3 PROJECT OBJECTIVE

The main objective of the project is to investigate the effect of specimen size on fracture toughness of mild steel. The specimen size was characterized into two parameter to be investigate:

1. The effect of specimen thickness on fracture toughness of carbon steel.
2. The effect of specimen notch depth on fracture toughness of carbon steel.

1.4 PROJECT SCOPE

- The general accepted measure of the fracture toughness of a metal is the plain strain fracture toughness, K_{IC} as measured by ASTM E399-74.However the specimen size required for valid measurement of K_{IC} need to refer ASTM E399-74 standards.
- In this project, fracture toughness will defined by perform the fracture toughness test by varying the specimen thickness and notch depth. The 27 specimens was fabricated by applying the machining process which is bandsaw machine, milling machine and wire-cut machine. The specimen was fabricating according to parameter decided that consist of 3 specimen for each different notch depth and thickness. Furthermore, by varying the notch depth, the relationship between fracture toughness and notch depth could be investigated.
- The method applied to analyzing and testing the specimens is three points bending test. The three point bending test involves bending a beam of the test material that has a notch depth across the beam at a position that is midway along the length of the bottom edge. The beam is supported at both ends, and then bent by driving a probe downward just above the notch using a universal testing machine (UTM).

CHAPTER 2

LITERATURE REVIEW

2.1 MILD STEEL

Steel is one of the major inventions that have helped mankind progress by leaps and bounds in many spheres. It is one of the most used and reused alloys. The advent of steel gave the industries the much needed momentum to grow and expand. Steel is now available in many grades and specifications. From all the types of steel, mild steel is the commonly found form. (William F.Smith, 2005)

Mild Steel is essentially a form of Carbon Steel that has low Carbon content which imparts the steel many physical and mechanical properties. It is used extensively for many Industrial applications including structural applications and constructions because of their properties. The properties of a material are determined by its composition. The material properties and mechanical characteristics of Mild Steel are crucial in deciding the area of application. These properties of the Mild Steel are determined by a series of tests. The popularity of mild steel in many industries is mainly because the material is easy to work with. The physical property of the mild steel is high malleability due to the low carbon content. As a result, steel is pliable as clay and so can be rolled and formed as required. This property enables the mild steel to be formed into bars. Mild steel also have high ductility that implies the steel can be bent into any shape or form without breaking. (S.R.Satish, 2003)

2.2 FRACTURE TOUHGNESS

Fracture toughness is an indication of the amount of stress required to propagate a pre-existing flaw. It is a very important material property since the occurrence of flaws is not completely avoidable in the processing, fabrication, or service of a material/component. Flaws may appear as cracks, voids, metallurgical inclusions, weld defects, design discontinuities or some combination thereof. Since engineers can never be totally sure that a material is flaw free, it is common practice to assume that a flaw of some chosen size will be present in some number of components and use the linear elastic fracture mechanics (LEFM) approach to design critical components. This approach uses the flaw size and features, component geometry, loading conditions and the material property called fracture toughness to evaluate the ability of a component containing a flaw to resist fracture. Fracture toughness is measured in terms of K_{IC} (plane-strain fracture toughness) where K stands for stress intensity factor at the crack tip, I- denotes that the fracture toughness test is performed in tensile mode and C denotes that the value of K is critical. When K attains critical value then crack propagation becomes unstable and results in fracture of the components. K_{IC} is a basic material property like yield strength. (NDT Resource Center, 2008)

According to (Matt Gordon, 1997), the fracture toughness can be predicted by using the equation of the minimum thickness of material before plain strain behavior occurs:

$$B = 2.5\left(\frac{K_{IC}}{\sigma_y}\right)^2 \qquad 2.1$$

B = minimum thickness to distinguish between K_C and K_{IC}

K_{IC} = fracture toughness, when the sample has a thickness less than B

σ_y = yield stress of material

(Matt Gordon, 1997), the fracture toughness of a material with a thickness equal to or greater than B, when it fractures in mode I. The expression used for determining K_{IC} is:

$$K_{IC} = Y\sigma\sqrt{\pi a} \quad 2.2$$

K_{IC} = fracture toughness, when the sample has a thickness greater than B

Y = constant related to the sample's geometry.

a = crack length (surface crack), one half crack length (internal crack).

σ = stress applied to the material.

In general, K_{Ic} is low for brittle materials and high for ductile materials. This trend is supported by the K_{Ic} values in Table 2.1 and 2.2 shown below.

Table 2.1: K_{IC} value for the different material

Material	$\boldsymbol{K_{IC}}$ **Mpa√m**
Metals	
2024-T351 Aluminum	36
4340 steel (tempered @ 260 C)	50
Titanium Alloy	44-66
Ceramics	
Aluminum Oxide	3.0-5.3
Soda-line glass	0.7-0.8
Concrete	0.2-1.4
Polymers	
Polymethyl Methacrylate (PMMA)	1
Polystyrene (PS)	0.8-1.1

Source: (Matt McMurtry, 1997)

Table 2.2: K_{Ic} value for the different material

Metal or Alloy	K_{IC} **Mpa√m**
Mild Steel	140
Medium-carbon steel	51
Rotor steel (A533; Discalloy)	204-214
Pressure vessel steels (HY130)	170
High-strength steel (HSS)	50-154
Cast iron	6-20
Pure ductile metals (e.g.. Cu,Ni,Ag,Al)	100-350
Be (brittle , hep metal)	4
Aluminum alloys (higt strength-low strength)	23-45
Titanium alloys (Ti 6Al 4V)	55-115

Source: (M.F. Ashby and D.R.H Jones, 1980)

K_{Ic} is a measure of a material's resistance to crack growth under a sustained monotonic loading condition. K_{Ic} is an extremely important parameter for structural design since structural components designed on the basis of plane strain fracture toughness are expected to survive in service without undergoing catastrophic failure. High cycle fatigue strength is another extremely important parameter for structural design. For failure prevention design in cyclic loading, very high fatigue strength or endurance limit is required. A combination of high fatigue strength and K_{Ic} is ideal for structural components because these characteristics will increase the working stress range and safety factor for load-bearing structural components. However, plane strain fracture toughness and high cycle fatigue strength have two conflicting requirements .It is well known that the K_{Ic} of a material decreases as the yield strength of the material increases. On the other hand, for very high endurance limit or high cycle fatigue strength, the yield strength must be high. Thus a combination of very high yield strength, fatigue strength and fracture toughness is difficult to obtain in most structural materials. (S.K. Putatunda, 2000).

(H.Wang et al, 2007) has evaluated the specimens perform three point bending test to get the fracture toughness. The two halves of the broken samples were used for the measurement of the notch depth *c* under an optical microscope. The length *c* was the average of the six values at three locations of the notch in the middle and at two lateral sides of each section. The toughness value was calculated according to the following formula:

$$K_{IC} = \frac{F_C}{B}\frac{S}{W^{\frac{3}{2}}} f\left(\frac{c}{W}\right) \tag{2.3}$$

$$f\left(\frac{c}{W}\right) = 2.9\left(\frac{c}{W}\right)^{1/2} - 4.6\left(\frac{c}{W}\right)^{3/2} + 21.8\left(\frac{c}{W}\right)^{5/2} - 37.6\left(\frac{c}{W}\right)^{7/2} + 38.7\left(\frac{c}{W}\right)^{9/2} \tag{2.4}$$

Where,

*F*c : Critical load

B : specimen width

s : Supporting span

f (*c*/*W*): Stress intensity shape factor.

2.3 MATERIAL THICKNESS

Specimens having standard proportions but different absolute size produce different values for stress intensity, K_I. This results because the stress states adjacent to the flaw changes with the specimen thickness, *B* until the thickness exceeds some critical dimension. Once the thickness exceeds the critical dimension, the value of K_I becomes relatively constant and this value, K_{IC}, is a true material property which is called the plane-strain fracture toughness. The relationship between stress intensity K_I, and fracture toughness, K_{IC} is similar to the relationship between stress and tensile stress. The K_I, represents the level of “stress” at the tip of the crack and the fracture toughness,K_I is the highest value of stress intensity that a material under very specific (plane-strain) conditions that a material can withstand without fracture. As the stress intensity factor reaches the K_{IC} value, unstable fracture occurs. The relation between the fracture toughness, K_{IC} and thickness is shown in Figure 2.1. (NDT Resource Center, 2008)

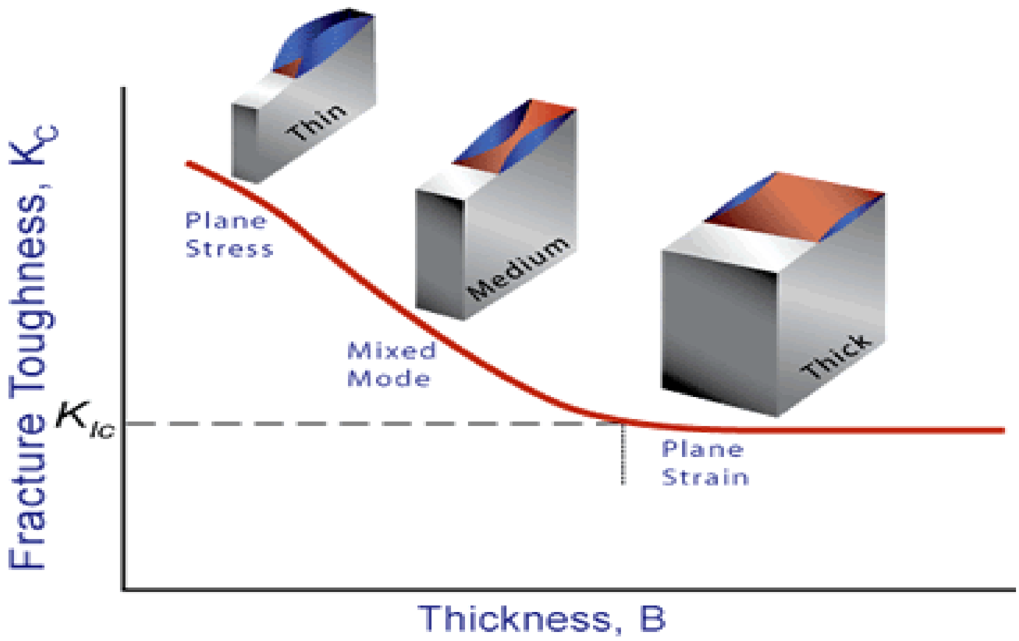

Figure 2.1: Graph Fracture Toughness, K_{IC} against Thickness, B

Source: (NDT Resource Center, 2008)

The critical stress-intensity factor, K_C at which unstable crack growth occurs for conditions of static loading has been generally recognized to be dependent on the thickness of the test specimen as shown in Figure 2.2. Many models have been proposed to establish quantitatively a basis for predicting this experimentally observed dependency between the fracture toughness, K_C and specimen thickness, B. (M.O. Lai. et.al, 1986)

From an energy balance of the fracture process, the total critical fracture energy, K_C is essentially the sum of the fraction of energy dissipated in shear lip formation and the fraction of energy dissipated in square fracture. The total fracture energy per unit fracture area is:

$$E_T = E_S + E_F \tag{2.4}$$

E_T = total fracture energy per unit fracture area.

E_S = fracture energy of the shear lip per unit area.

E_F = flat fracture regions per unit area

According to (M.O.Lai.et.al, 1986), assumed that the critical specimen thickness, *Bo*, is independent of the specimen thickness and flat fracture is a surface phenomenon. The fracture toughness resulting from this model can be shown to be:

$$K_C^2 = \frac{1}{2}\, EK_S B_O \left(\frac{B_O}{B}\right) + EK_f \left(1 - \frac{B_O}{B}\right) \qquad for\ \frac{B}{B_O} > 1 \tag{2.5}$$

$$K_C^2 = \frac{1}{2}\, EK_S B_O \left(\frac{B_O}{B}\right) \qquad for\ \frac{B}{B_O} \leq 1 \tag{2.6}$$

E = Young's modulus

K_S and K_f = Constants to be evaluated experimentally.

Bo = Critical specimen thickness

(M.O. Lai et.al, 1986) is making similar assumptions, the model gives:

$$K_C = S^2\, K_{C,Max} + (1 - S)K_{IC} \tag{2.7}$$

S = fractional part of the fracture surface occupied by shear lips

$K_{C,Max}$ = the value of K_C at $B = B_O$

K_{IC} = the limiting plane strain fracture toughness as shown in Figure 2.2.

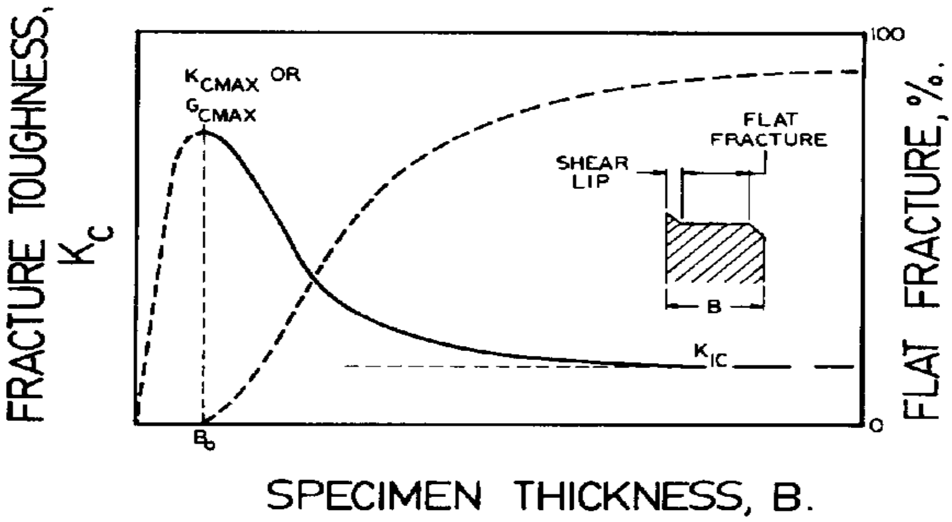

Figure 2.2: Dependence of fracture toughness on specimen thickness

Source: (M.O. Lai et.al, 1986)

(M.O.Lai et.al, 1984) has evaluated the relationship between specimen thickness *B* and the fracture toughness, *Kc* of the material Aluminum Alloy 7075-T6 is shown in Figure 2.3. *Kc* was calculated from the load-displacement at Figure 2.4 record at the point of maximum load and the corresponding crack length.

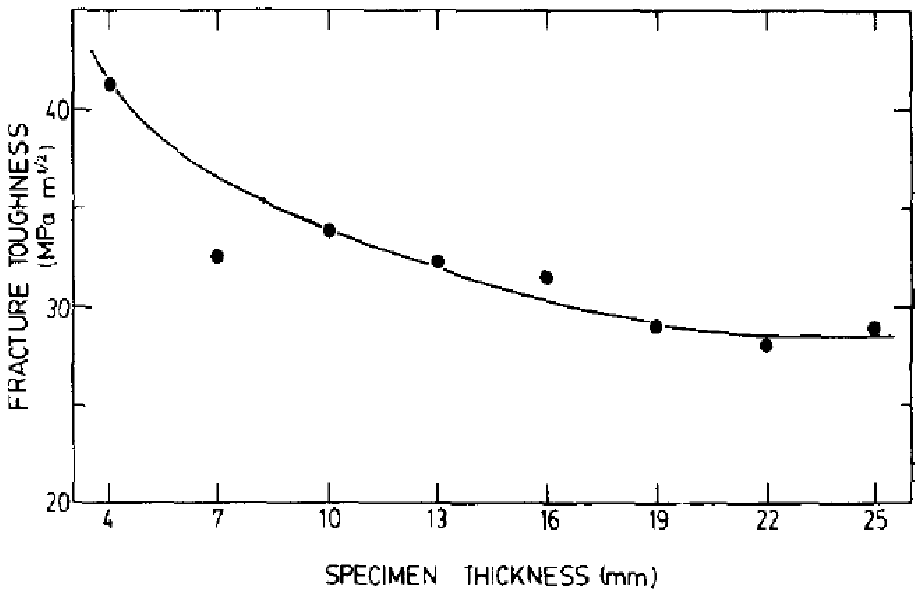

Figure 2.3: Relationship between the fracture toughness and the specimen thickness

Source: (M.O. Lai et.al, 1984)

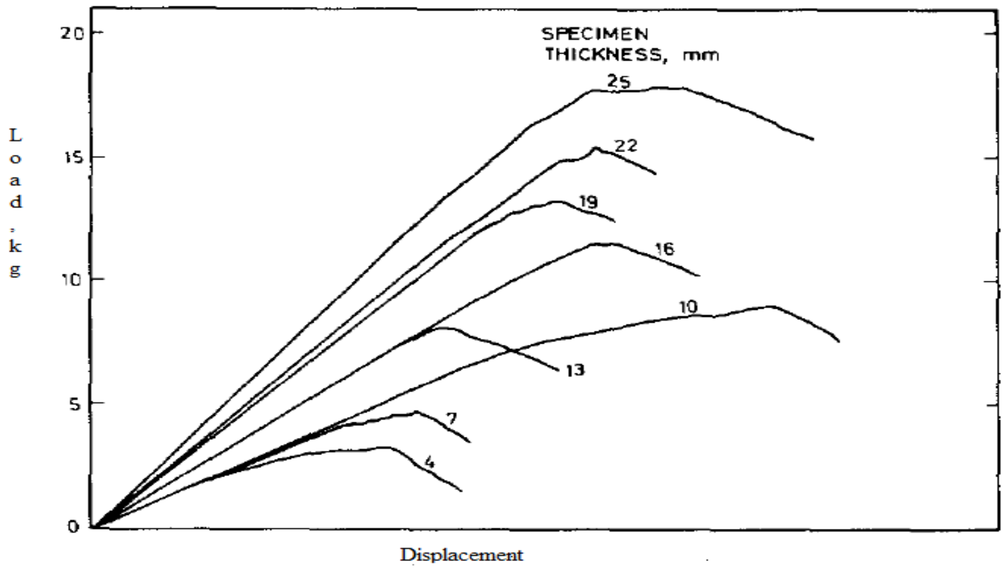

Figure 2.4: Effect of specimen thickness on the load-displacement records.

Source: (M.O. Lai et.al, 1984)

2.4 NOTCH DEPTH

The effect of notch root radius on fracture toughness measurements purpose to show that there is a linear dependence between the square root of the notch depth, ρ, and the apparent fracture toughness, $K_{I,app}$, provided that the notch depth is greater than some critical value. Below this critical value the measured value of the fracture toughness is sensibly constant. However, none of these results is for a root radius greater than one millimetre. This is particularly pertinent in view of the fact that none of the experimental results convincingly shows the linear dependence. The purpose of this is twofold is to avoids the "cut off' which occurs at small root radii and it extends the existing data into a region where any departure from a linear dependence of $K_{I,app}$ on $\sqrt{\rho}$ can easily be detected. (T. Fett*, 2005)

(G. M. Spink.et.al, 1973) was evaluate the stress required to propagate fracture from a semi-elliptical notch of semi-major axis c and semi-minor axis b (notch radius $\rho = b^2/c$) in a semi-infinite medium. His result, which applies to a state of anti-plane strain deformation, may be written:

$$\frac{\sigma_f}{\sigma_u} = \frac{1}{\left[1+\left(\frac{\rho}{c}\right)^{\frac{1}{2}}\right]}\left\{\frac{2}{\pi}\, sec^{-1}\left[\exp\left(\frac{\pi K_{1c}^2}{8\sigma_u^2 c}\right)\right] + \left(\frac{\rho}{c}\right)^{\frac{1}{2}}\right\} \tag{2.8}$$

K_{Ic} : Fracture toughness

σ_u : Stress at which an unnotched specimen would fail

ρ : Notch Radius

c : Notch depth

This result is assume valid for plane strain stress systems, hence we identify K_{IC} with the plane strain fracture toughness and σ_u is the stress at which an unnotched specimen would fail. The ratio σ_f/σ_u, is to be calculated appropriate to the testing conditions. The appropriate value of the ultimate stress in bend is difficult to estimate although experimental results indicate that it is approximately twice the value in tension. If $\left(\frac{K_{1c}}{\sigma_u} \ll 1\right)$ and we have a small scale yielding situation then equation (2.9) reduces to:

$$\sigma_f = \frac{K_{1c} + \sigma_u(\pi\rho)^{\frac{1}{2}}}{(\pi\rho)^{\frac{1}{2}}\left[1+\left(\frac{\rho}{c}\right)^{\frac{1}{2}}\right]} \tag{2.9}$$

Equation (2.8) may be written in the equivalent form:

$$K_{I,ap} = \frac{K_{IC} + \sigma_u(\pi\rho)^{\frac{1}{2}}}{\left[1+\left(\frac{\rho}{c}\right)^{\frac{1}{2}}\right]} \tag{2.10}$$

K_{Ic} : Fracture toughness

σ_u : Stress at which an unnotched specimen would fail

ρ : Notch Radius

c : Notch Depth

This equation relates the apparent fracture toughness, $K_{I,\,app}$, measured on a specimen with a blunt notch, to the material properties K_{IC} and σ_u.

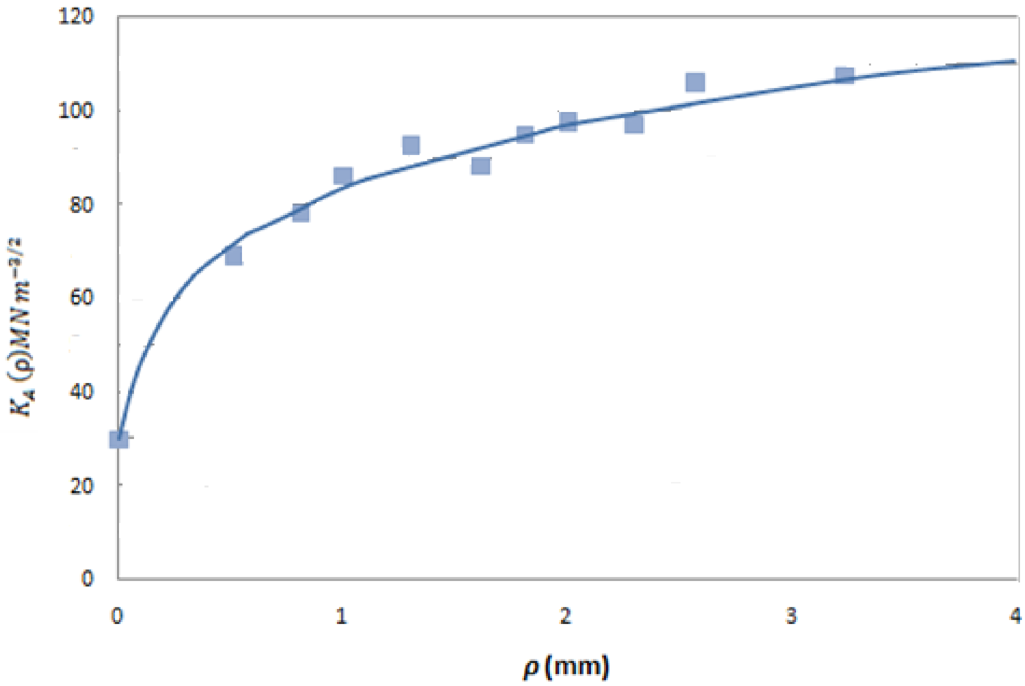

Figure 2.5: The apparent fracture toughness as a function of the notch root radius; the experimental points are compared with equation (2.10).

Source: (G. M. Spink.et.al, 1973)

The maximum load for each specimen is obtained and plotted as a function of the notch depth for different *a/W* (in Figure 2.6).The data show that the maximum load P_{max} increases linearly with the notch radius ρ and decreases as *a/W* increases. (Mourad A.H .I, 2011)

The maximum loads are used to calculate the apparent fracture toughness $K_{I,app}$ by using the following equation :

$$K_{I,app} = \frac{f_1\left(\frac{a}{W}\right)P_{max}}{B(W-a)} \tag{2.11}$$

$f_1\ (a/W)$: Geometrical function
B : Specimen thickness
W : Specimen width.

The results are used to plot $K_{I,app}$ vs ρ for different values of *(a/W)* as shown in Figure 2.6. The results show that $K_{I,app}$ is dependent on ρ and *a/W* ratio. $K_{I,app}$ is almost constant in the range from ρ = 0.08 mm up to 0.16 mm for all *a/W* ratio. Then it increases almost in a linear relationship up to ρ ~ 0.6 mm for *a/W* ratio from 0.1 up to 0.6, prior it starts to increase nonlinearly with ρ up to ρ = 3 mm. However, for *a/W* = 0.7 up to 0.9, $K_{I,app}$ increases linearly in the range from ρ >0.16 up ρ ~ 0.25 mm prior it increases nonlinearly with p up to ρ =3 mm. That linear increase has been reported by some researchers. $K_{I,app}$ reaches a minimum value ($K_{Ic,app}$) when ρ reaches its minimum value (ρ = 0.08 mm), however, there is a critical notch radius value p_c for each *a/W* below which $K_{I,app}$ becomes almost independent of ρ. Therefore, the curves in Figure 2.7 consist of three regions I, II and III. In the region I there is a rapid decrease in $K_{I.app}$ followed by less rate of decrease in the region II prior the curve becomes almost a horizontal line (or reaches a lower plateau) in the region III ,$K_{I,app}$ reaches $K_{Ic.app}$ at ρ =0.16 up to 0.08 mm. A critical notch root radius below which fracture toughness is independent of ρ has been reported. (Mourad A.H .I, 2011)